Determining Resilient Modulus of Subgrade Materials for Mechanistic-Empirical Design

Prepared for
North Central Pavement Research Coordination Partnership

Prepared by
CTC & Associates LLC
WisDOT Research & Library Unit
July 30, 2007

Request for Report

The North Central Pavement Research Coordination Partnership requested a synthesis report on determination of subgrade resilient modulus for use in mechanistic-empirical design. The request was for a standard synthesis report of current research and practice in measuring resilient modulus combined with a review of partner state research on resilient modulus drawn from the Frozen Four Web site at http://www.frozenfour.us/. The report will be used as a primer in anticipation of the October 2007 meeting that will include a workshop on resilient modulus of subgrade for mechanistic-empirical design.

Summary

A review of national databases as well as the Frozen Four Web site shows widespread interest in modifying or reducing reliance on AASHTO resilient modulus laboratory testing procedure TP46-94, which uses the triaxial compression test. The method is considered expensive, time-consuming, and susceptible to variable results within and between testing facilities. The Frozen Four will seek to identify a regional test or standard for assessing resilient modulus of subgrade materials for use in mechanistic-empirical design, a method that can benefit from sharing data and research.

This report looks at resilient modulus of subgrade according to the three areas that will be discussed in the October 2007 Frozen Four workshop: **Data** collection, **Measurement** methods, and **Prediction** models and correlations between tests and soil properties or indices. We have provided hyperlinks to documents that are available online; other documents may be available through your DOT library.

Data

This section cites studies that produced data on resilient modulus of subgrade soils for use in mechanistic-empirical design. These studies focused more on characterization and data production than on developing correlations between resilient modulus and other soil properties or tests. The studies include a pooled fund project in progress, an ongoing study in Kentucky, and two completed studies each from Minnesota and Wisconsin.

In Progress – Pooled Fund Study TPF-5(129), "Recycled Unbound Pavement Materials" (MnROAD study)
http://www.pooledfund.org/projectdetails.asp?id=361&status=4
This study focuses not on soils but on recycled base materials such as crushed concrete and recycled asphalt pavement. The focus on design properties of various materials includes evaluation of resilient modulus.
Contact: Nancy Whiting, nancy.whiting@dot.state.mn.us.
Frozen Four: Minnesota, Lead Agency.

Kentucky
In Progress – "Resilient Modulus of Compacted, Crushed Stone Aggregate Bases"
http://rip.trb.org/browse/dproject.asp?n=6856
This research seeks to determine the resilient modulus of various compacted, crushed aggregate bases used for highways in Kentucky. Equipment and software was upgraded, and triaxial tests performed on several samples.
Contact: Marcie Carr, Kentucky Transportation Cabinet, (502) 564-3730. Investigator: Tommy Hopkins, (859) 257-4513, thopkins@engr.uky.edu.

Minnesota (from Frozen Four database)
"Small Strain and Resilient Modulus Testing of Granular Soils," Peter Davich, Joseph Labuz, Bojan Guzina and Andrew Drescher, Mn/DOT Report 2004-39, August 2004.
http://www.lrrb.org/pdf/200439.pdf
Researchers determined resilient modulus, shear strength, dielectric permittivity, and shear and compressional wave speed for 36 soil specimens from six samples. At low moisture levels, soils had higher stiffness but also more non-uniformity in displacement measurements. Researchers present a hyperbolic model for strain-dependent modulus reduction of base and subgrade materials, allowing field testing at small strains to estimate resilient modulus.

"Characterization of the Subgrade Soils at the Minnesota Road Research Project," David Newcomb, David Van Deusen and Thomas Burnham, MN/RD 94-19, June 1994.
http://mnroad.dot.state.mn.us/research/MnROAD_Project/MnRoadReports/MnRoadOnlineReports/94-19.pdf
This study sought to characterize embankment and granular base soils at MnROAD. FWK, deflection data, jarred, bagged and thin-walled soil samples, and other methods were employed. Deflection and FWD data was used to backcalculate elastic modulus for homogenous and multi-layered systems, methods enhance with geostatistical analysis. Lab results on thin-walled samples compared well with backcalculated values from outermost site sensors, but inner sensor deflections varied and were generally lower than outer sensors. Measured deflections varied highly with surface irregularities, density variations, and moisture content.

Wisconsin (from Frozen Four database)
"Determination of Typical Resilient Modulus Values for Selected Soils in Wisconsin," Hani Titi, Mohammed Elias and Sam Helwany, WHRP 0092-03-11, June 2006.
http://www.whrp.org/Research/Geotechnics/geo_0092-03-11/WHRP%2003-11%20Determination%20of%20Typical%20Resilient%20Modulus%20Values%20for%20Selected%20Soils%20in%20Wisconsin.pdf
Based on a study of 19 soil samples, research showed the AASHTO triaxial test methods were effective for fine-grained and coarse-grained soils, if considered separately, and led to estimates that were more accurate than previous models that were based on data from the Long-Term Pavement Performance program. Data was provided for use in level 3 mechanistic-empirical design, and model equations were developed for use with level 2 design (which includes testing of basic soil properties). An FY 2008 study will expand the data sets to include more soil samples.

"Determination of Influences on Support Strength of Crushed Aggregate Base Course Due to Gradational, Regional and Source Variations," Paul Eggen and Donald Brittnacher, WHRP 0092-02-01, February 2004.
http://www.whrp.org/Research/publications/Final%20Reports/WHRP%2004%2008%20Determination%20of%20Influences%20on%20Support%20Strength%20of%20Crushed%20Aggregate%20Base%20Course%20Due%20to%20Gradual,%20Regional,%20and%20Source%20Variations.PDF
Researchers determined resilient modulus values of 36 aggregate samples from Wisconsin. Attempts to correlate physical characteristics and simple tests with resilient modulus were unsuccessful. Various physical and source characteristics did not correlate with variation in resilient modulus values in any predictable way. Generally, resilient modulus was higher for limestones and carbonates, and lower for granites, but quarry-sourced and pit-sourced aggregates did not differ significantly by source. Age of source also did not correlate with value variations.

Measurement

The standard method for laboratory measurement of resilient modulus is the AASHTO triaxial test procedures. In-situ methods may include dynamic cone penetrometer testing, falling weight deflectometer testing, and various load plate tests and bearing ratios. This section first lists studies related to the AASHTO standard and efforts to improve it, followed by research on specific in-situ methods.

Laboratory – Triaxial Method

This section includes a select number of recent research projects focused on methods for improving use of the AASHTO standard, triaxial tests of unbound materials. We list national and regional research first, then studies from Indiana and Minnesota.

"Laboratory Determination of Resilient Modulus for Flexible Pavement Design," Matthew Witczak, *Research Results Digest*, No. 285, January 2004.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rrd_285.pdf
This document offers a brief technical description of NCHRP research on resilient modulus and its laboratory testing for both bituminous mixtures and unbound subgrade materials. Appendix 2 focuses on subgrade materials and the triaxial test method for determining resilient modulus; see pages 12-30.

LTPP Protocol P46: Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils, August 1996.
http://www.tfhrc.gov/pavement/ltpp/pdf/p46.pdf
This is the program protocol that adopts AASHTO resilient modulus test procedures. It reviews AASHTO and ASTM standards in its own protocols and describes materials required, testing apparati, testing procedures, calibration and calculations.

"Harmonized Resilient Modulus Test Method for Unbound Pavement Materials," Andrei Dragos, Matthew Witczak, Charles Schwartz and Jacob Uzan, *Transportation Research Record No. 1874,* 2004: 29-37.
Researchers present a new laboratory test protocol for measuring unbound materials. Following evaluation of 13 predictive models and 25 sets of resilient modulus test data, researchers developed a method for measuring resilient modulus that is a hybrid of four state-of-the-art test procedures enhanced with more accurate stress-dependent resilient modulus predictive equations.

In Progress – Pooled Fund Study, TPF Solicitation 1140, "Improving Resilient Modulus (MR) Test Procedures for Unbound Materials."
http://www.pooledfund.org/projectdetails.asp?id=1140&status=1
This research will look closely at reducing or eliminating lab testing variability through precision and bias studies of testing. It uses the LTPP guide for determining resilient modulus of unbound materials, and a CD-ROM from LTPP that provides testing procedures and videos introducing resilient modulus testing, demonstrating the testing process and more. The CD-ROM includes an interactive tutorial developed with help from Mn/DOT. WisDOT is one of eight member states for the five-year project beginning in 2007.
Contact: Mike Moravec, mike.moravec@fhwa.dot.gov.
Frozen Four: Wisconsin, Participating Agency.

Indiana

"Resilient Behavior of Compacted Subgrade Soils Under the Repeated Triaxial Test," Daehyeon Kim and Jong Ryeol Kim, *Construction and Building Materials*, Vol. 21 (7), July 2007: 1470-1479.
Researchers employed a simplified version of the triaxial test, one that limits testing to a select number of confining pressures and deviator stresses. On Indiana sandy-silty-clay and silty-clay subgrade soils, results compared well with the AASHTO standard of 15 combinations of stresses.

"Simplification of Resilient Modulus Testing for Subgrades," Daesuk Kim, project end date December 2005. See the project abstract at http://rip.trb.org/browse/dproject.asp?n=13490.
In work for Indiana DOT, Purdue University's Kim evaluated resilient modulus and strain behavior on 14 cohesive soils and five cohesionless soils from Indiana using the DCP and various compressive tests to help develop a way to simplify the AASHTO triaxial test method by reducing the numbers of steps and cycles required. This research seems likely to be the precursor to the July 2007 Indiana DOT study above.

Minnesota (from Frozen Four database)
"Resilient Modulus Testing of Materials from Mn/ROAD, Phase I," Richard Berg, Susan Bigl, Jeffrey Stark and Glenn Durell, Mn/RC 96-21, September 1996.
http://mnroad.dot.state.mn.us/research/MnROAD_Project/MnRoadReports/MnRoadOnlineReports/96-21.pdf
Researchers from the U.S. Army Cold Regions Research and Engineering Laboratory tested samples from MnROAD on Mn/DOT's behalf. Samples included lean clay subgrade and two extreme base grades, and were tested in frozen and thawed condition, then compared to samples tested without having been frozen. Data was used to prove equations predicting frozen modulus based on unfrozen water content, and unfrozen modulus based on stress, saturation and density. The results were used in developing a CRREL mechanistic design procedure.

Field – Dynamic Cone Penetrometer
The following studies focus on the use of the dynamic cone penetrometer for in-situ subgrade evaluation and determination of resilient modulus. Research from Louisiana—a leader in the evaluation of the DCP and other methods including falling weight deflectometers, the California Bearing Ratio, and plate load tests for determining subgrade resilient modulus—is followed by projects from Mississippi.

Louisiana
"Soil Parameters for Pavement Design and Subgrade Resilient Modulus: Application of Dynamic Cone Penetrometer in Pavement Construction Control," Murad Y. Abu-Farsakh, Munir D. Nazzal, Khalid Alshibli and Ekram Seyman, *Transportation Research Record* 1913, December 2006: 52-61.
Researchers compared laboratory and field test results from the DCP with three reference tests: FWD, CBR and the plate load test. Regression analyses were verified in field tests, and researchers found reliable correlations.

"Development of Resilient Modulus Prediction Models for Base and Subgrade Pavement Layers from In Situ Test Results," Ravindra Gudishala, Louisiana State University M.S. thesis, December 2004.
http://etd.lsu.edu/docs/available/etd-11112004-161757/unrestricted/Gudishala_thesis.pdf
This master's thesis from LSU presents correlations between lab triaxial tests and in-situ tests with the Geogauge, FWD and DCP, finding good agreement between predictions and measured values.

Mississippi
"Automated Dynamic Cone Penetrometer for Subgrade Resilient Modulus Characterization," Ashraf M. Rahim and K.P. George, *Transportation Research Record No. 1806*, 2002: 70-77.
Testing on soil samples and at 12 field sites in Mississippi found that DCP index could be correlated in different ways for fine-grained and coarse-grained soils, and that regression models could be improved by testing for other physical properties.

Field – Falling Weight Deflectometer
These studies focus on the use of falling weight deflectometers for in-situ evaluation of subgrades for resilient modulus. As with the DCP evaluations above, many studies compare FWD to other methods, such as lab triaxial methods, various bearing ratio methods, and more. This section includes research from Florida, Minnesota, Mississippi and Virginia.

Florida
"Measuring Resilient Modulus of Subgrade Materials for Design of Pavement Structures," W. Virgil Ping and Zenghai Yang, *GeoShanghai 2006: Pavement Mechanics and Performance, 2006*: 189-194. See the project summary at http://www.dot.state.fl.us/research-center/Completed_Proj/Summary_RD/FDOT_780.pdf.
Investigators present results from a multiyear effort in Florida to correlate field and laboratory resilient modulus measurements, including a case study validating flexible pavement design using the procedures. The study focuses on both subgrade and flexible pavement resilient modulus. Findings include:

- FWD backcalculated moduli were 1.8 times higher than laboratory measurements.
- Embankment soil measurements should be done with standard Proctor compaction.

"Design Subgrade Resilient Modulus for Florida Subgrade Soils," Nishantha Bandara and Geoffrey M. Rowe, *ASTM Special Technical Publication No. 1437*, 2002: 85-96.
Florida researchers developed preliminary relationships for design subgrade resilient modulus via FWD and Lime Rock Bearing Ratio tests.

Minnesota (from Frozen Four database)
"Initial Characterization of Subgrade Soils and Granular Base Materials at the Minnesota Road Research Project," David Newcomb, Bruce Chadbourn, David Van Deusen and Thomas Burnham, MN/RC-96-19, December 1995.
http://mnroad.dot.state.mn.us/research/MnROAD_Project/MnRoadReports/MnRoadOnlineReports/96-19.pdf
Testing at MnROAD in 1994 included both FWD and DCP examinations compared with LTPP laboratory resilient modulus values. FWD results showed high variability due to varying surface conditions, soil moisture content, density and other conditions. DCP results compared well with laboratory values, but no correlations were identified.

Mississippi
"Falling Weight Deflectometer for Estimating Subgrade Elastic Moduli," Ashraf M. Rahim and K.P. George, *Journal of Transportation Engineering*, Vol. 129 (1), January/February 2003: 100-107.
Researchers compared FWD measurements with laboratory tests before and after construction of pavements, finding that backcalculated moduli of prepared subgrades agreed with laboratory results. They found that backcalculated modulus increased 40 percent for fine-grained soils based on deflection testing of finished pavement, and 100 percent for coarse-grained soil. A study of 20 pavement sections substantiated these results, casting doubt on the AASHTO backcalculated moduli adjustments.

"Subgrade Characterization Employing the Falling Weight Deflectometer," K.P. George, Manil Bajracharya and Richard Stubstad, *Transportation Research Record No. 1869*, 2004: 73-79.
Researchers explored a method for correlating FWD moduli with triaxial test laboratory moduli in a selected pattern on subgrade sections to ensure accuracy even in conditions of nonhomogenous subgrades.

Virginia
"Relationship Between Backcalculated and Laboratory-Measured Resilient Moduli of Unbound Materials," Gerard W. Flintsch, Imad L. Al-Qadi, Youngjin Park, Thomas L. Brandon and Alexander Appea, *Transportation Research Record No. 1849*, 2003: 177-182.
Researchers found strong correlations between laboratory resilient modulus tests and backcalculated resilient modulus values from in-situ FWD measurements for unbound granular materials from 12 sites.

Field – Seismic Test
A novel approach from Texas uses a seismic test method for assessing resilient modulus of subgrade materials.

Texas
"A Simple Method for Determining Modulus of Base and Subgrade Materials," Soheil Nazarian, Deren Yuan and Robert R. Williams, *ASTM Special Technical Publication No. 1437*, 2002: 152-164.
Researchers correlated a quick seismic field test with time-consuming resilient modulus tests.

Prediction
Prediction of resilient modulus for design purposes necessarily entails the triaxial laboratory test and a number of in-situ tests, but also includes correlations of test results with soil properties. The goal is to simplify the testing requirements by establishing correlations between various test results and soil properties so that designers may use AASHTO mechanistic-empirical design methods at levels 2 and 3, which require a lower order of site-specific data. These methods allow designers and engineers to reduce their reliance on the expensive, time-consuming and difficult process of testing resilient modulus. This section includes research from Arkansas and Louisiana, a significant body of work from Mississippi, a novel approach from Ontario, and an NCHRP synthesis report that is in progress.

Arkansas
In Progress – "Estimating Subgrade Resilient Modulus for Pavement Design"
http://rip.trb.org/browse/dproject.asp?n=9447
The Arkansas State Highway and Transportation Department conventionally avoids resilient modulus testing to avoid the equipment and expenses associated with the process. Previous estimation methods have been proven insufficient, however, and this project seeks to develop material models that correlate soil index properties with resilient modulus values. The method to emerge will be a less expensive and difficult route to developing resilient modulus inputs for design purposes.
Contact: Karen McDaniels, (501) 569-2580, karen.mcdaniels@ahtd.state.ar.us.

Louisiana
"The Use of Dynamic Cone Penetrometer to Predict Resilient Modulus of Subgrade Soils," Ananda Herath, Louay N. Mohammad, Kevin Gaspard, Ravindra Gudishala and Murad Y. Abu-Farsakh, *Geotechnical Special Publication No. 130-142, Geo-Frontiers 2005*, 2005: 17-32.
Researchers attempted to develop predictive correlations between lab resilient modulus tests of cohesive soils, DCP test results, soil types, dry unit weights and moisture contents, and found DCP test results to be a strong predictor.

Mississippi
"Models to Estimate Subgrade Resilient Modulus for Pavement Design," A.M. Rahim and K.P. George, *International Journal of Pavement Engineering*, Vol. 6 (2), June 2005: 89-96.
Researchers evaluated data from two field-test programs in Mississippi to develop correlation equations between lab moduli and stress states for fine- and coarse-grained subgrade soils. Two developed models were verified through comparison to field data.

"Subgrade Soil Index Properties to Estimate Resilient Modulus for Pavement Design," A.M. Rahim, *International Journal of Pavement Engineering*, Vol. 6 (3), September 2005: 163-169.
Based on the Mississippi field sites, the researcher presented correlations between select soil properties and resilient modulus values for fine- and coarse-grained subgrade soils separately. The correlations agreed satisfactorily for use in level 2 and 3 AASHTO design methods.

"Resilient Modulus Estimation System for Fine-Grained Soils," Yuh-Puu Han, Thomas M. Petry and David N. Richardson, *Transportation Research Record No. 1967*, Geology and Properties of Earth Materials, 2006: 69-77.
This paper presents a software tool that estimates resilient modulus of fine-grained subgrade soils based on data inputs from a user. Data is evaluated for reasonableness and accuracy, and then the software uses certainty rules to cull four estimation models from 30 that a user may select from for estimating resilient modulus.

"Resilient Modulus of Subgrade Soils A-1-b, A-3, and A-7-6 Using LTPP Data: Prediction Models with Experimental Verification," Shraddha Joshi and Ramesh B. Malla, *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*, Vol. 2006: 233.
This paper offers prediction models for three AASHTO subgrade soil types developed from multiple linear regression analyses of LTPP data for 82 test specimens and over 1,200 resilient modulus values from a number of states and from Canada. Models and tests of A-1-b soil samples correlated particularly well.

Ontario, Canada
"Predicting the Resilient Modulus of Unbound Granular Materials by Neural Networks," M. Zeghal and W. Khogali.
http://irc.nrc-cnrc.gc.ca/pubs/fulltext/nrcc47704/nrcc47704.pdf
Researchers present a method for using artificial neural networks for initial estimates of subgrade resilient modulus for designs. The ANN technique proves effective as a quality control tool to eliminate data of questionable reliability, and confirms the influences of density, moisture content and deviator stress on resilient modulus. ANN can help designers reduce reliance on triaxial test methods.

NCHRP
Synthesis in Progress – NCHRP Project 20-5, Topic 38-09, Synthesis of Highway Practice: "Correlations for Resilient Modulus Values of Subgrades and Unbound Pavement Materials"
http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=113
This project is developing a synthesis report on national practice based on literature searches and surveys of state transportation agencies. It focuses on what testing methods agencies use, and what methods they use for predicting resilient modulus and/or correlating it to soil properties such as density, moisture content and soil classification, and to strength parameters determined by DCP, FWD, CBR and other methods. The second draft of the final report is currently under review, with approval and release expected before the end of 2007.
Contact: Jon Williams, TRB, (202) 334-3245 or jwilliams@nas.edu. PI: Anand Puppala, University of Texas-Arlington, (817) 272-5821, anand@uta.edu.